Tools for Dynamic Systems Analysis

Jeffrey Csank

NASA Glenn Research Center

Cleveland, OH, 44135

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Team

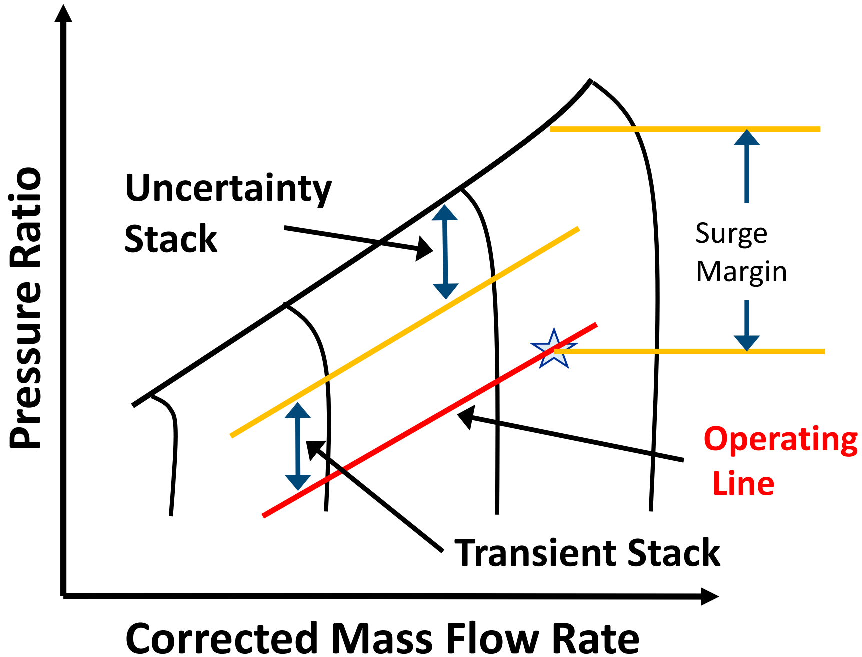
- Research and Engineering Directorate(L):
  - Propulsion Division (LT)
    - Propulsion Systems Analysis Branch (LTA)
      - William Haller
      - Jeffrey Chin
      - Thomas Lavelle
  - Communication and Intelligent Systems Division (LC)
    - Intelligent Control and Autonomy Branch (LCC)
      - Jeffrey Csank
      - George Thomas (N&R Engineering)
      - *Alicia Zinnecker (N&R Engineering)*
- *Georgia Tech*
  - *Metin Ozcan, Chris Perullo, Jimmy Tai*

Outline

- Introduction
- Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)
  – Features of the tool
  – Application to C-MAPSS40k
- Mechanism for analyzing turbine engine dynamic performance
- Methodology to assess engine designs to closed-loop performance and operability requirements
  – Application to C-MAPSS40k
- Benefits
- Summary

Introduction

- Current engine design constraints are based on steady-state data and “worst-case” operating assumptions.



Operating Line

- Most efficient operation while meeting design constraint.

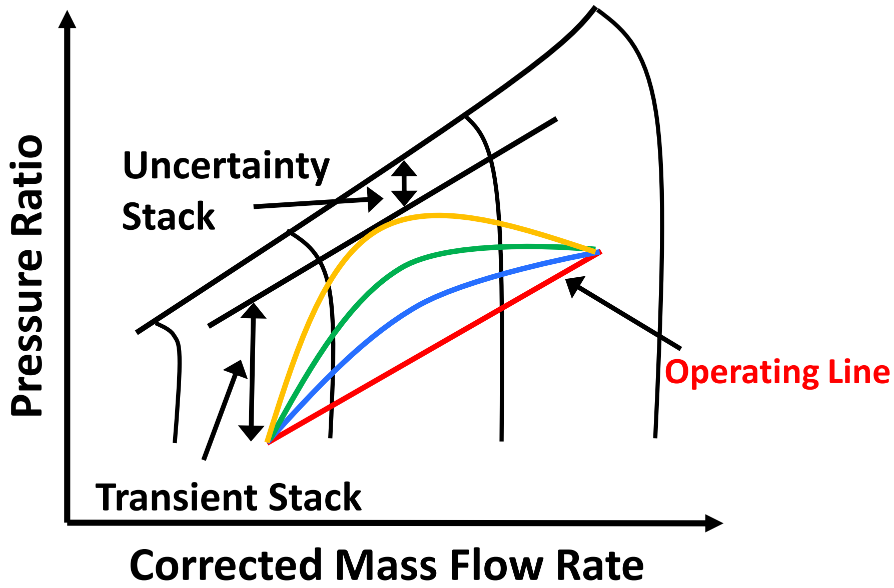
Uncertainty Stack

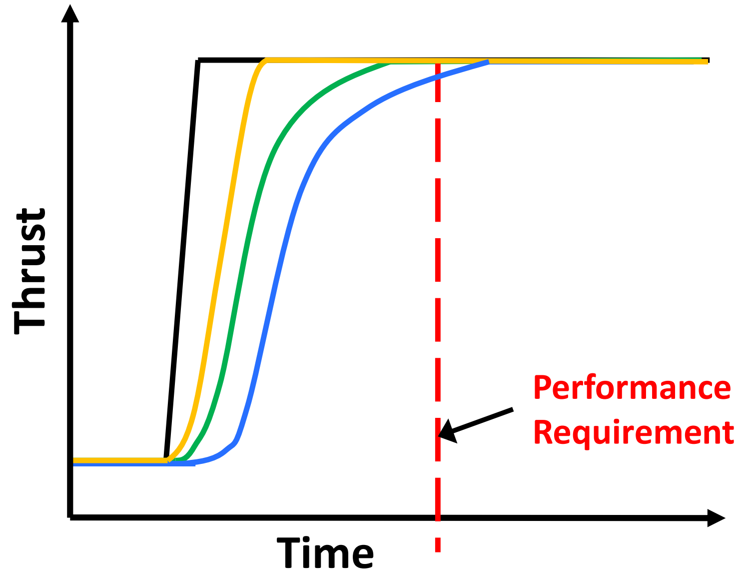
- Mechanical imperfections, inlet distortion, engine degradation, etc.

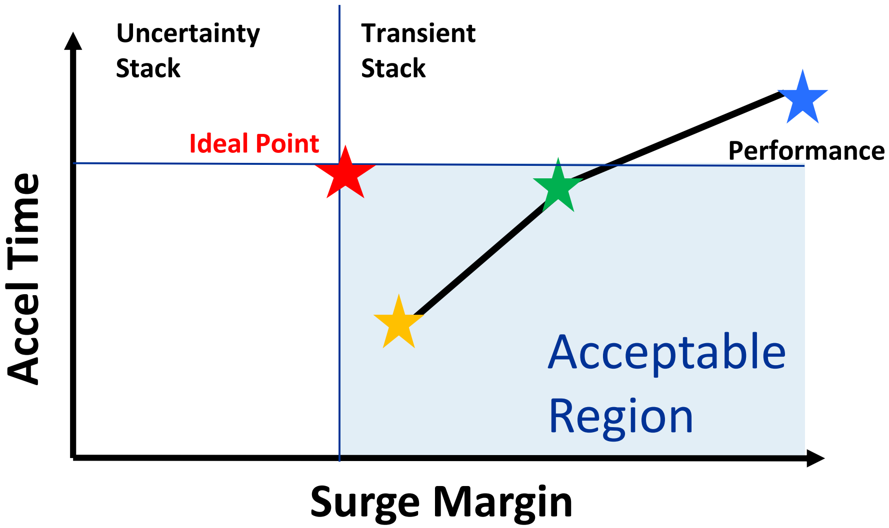
Transient Allowance

- Occurs while transitioning from one point to anther.

Introduction







Help balance performance and operability. Overly conservative margins may be traded in for increased efficiency.

Introduction

- Control design considers **trade-off** between *performance* (time-response) and *operability* (surge margins)
  - Time response is the time required to transition from idle to 95% max thrust for step-change (requirement < 5 seconds)
  - **Faster engine response** necessarily requires operating **closer to surge line**
  - Must balance trade-off through controller design specifications

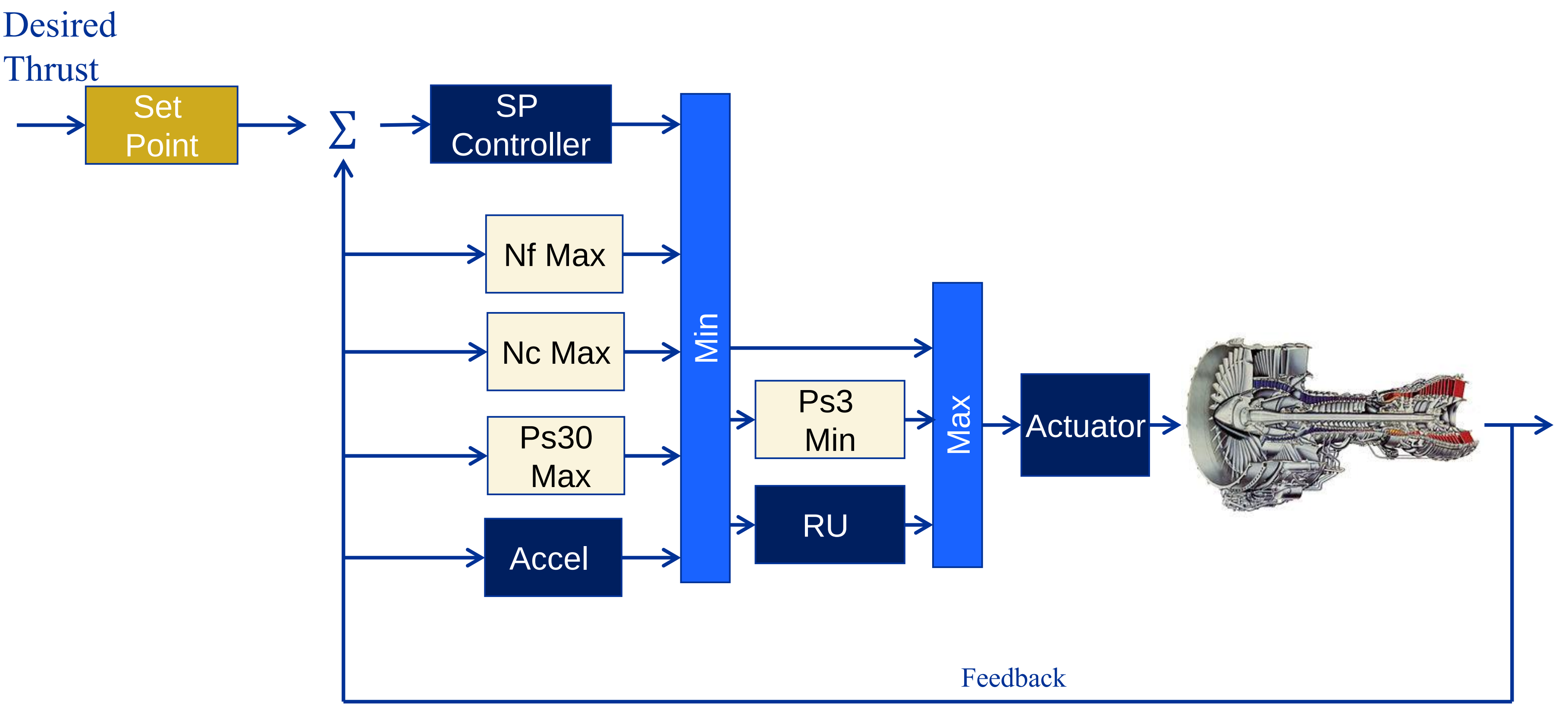
Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)

- **Provide an estimate of the closed-loop transient performance/capability of a conceptual engine design.**
  - Released under the NASA Github page: https://github.com/nasa/TTECTrA/releases

- Capable of automatically designing a controller for transient operation (subset of full controller).

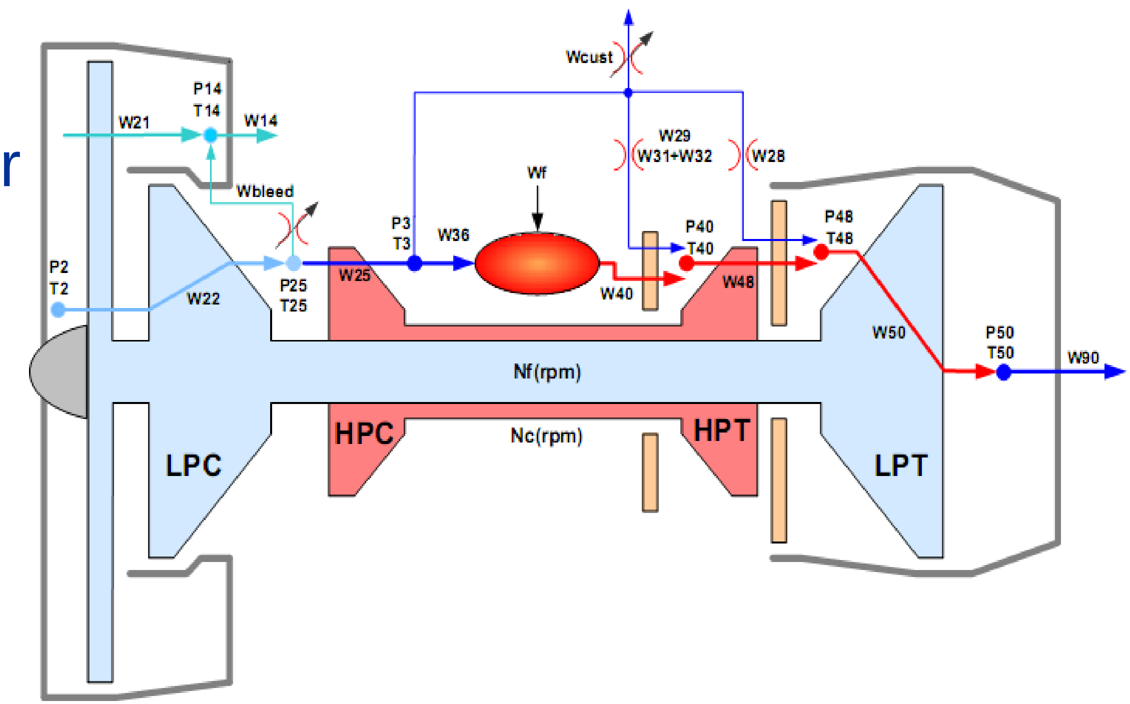
- Easily integrates with a users engine model in the MATLAB®/Simulink® Environment.

TTECTrA Control Architecture

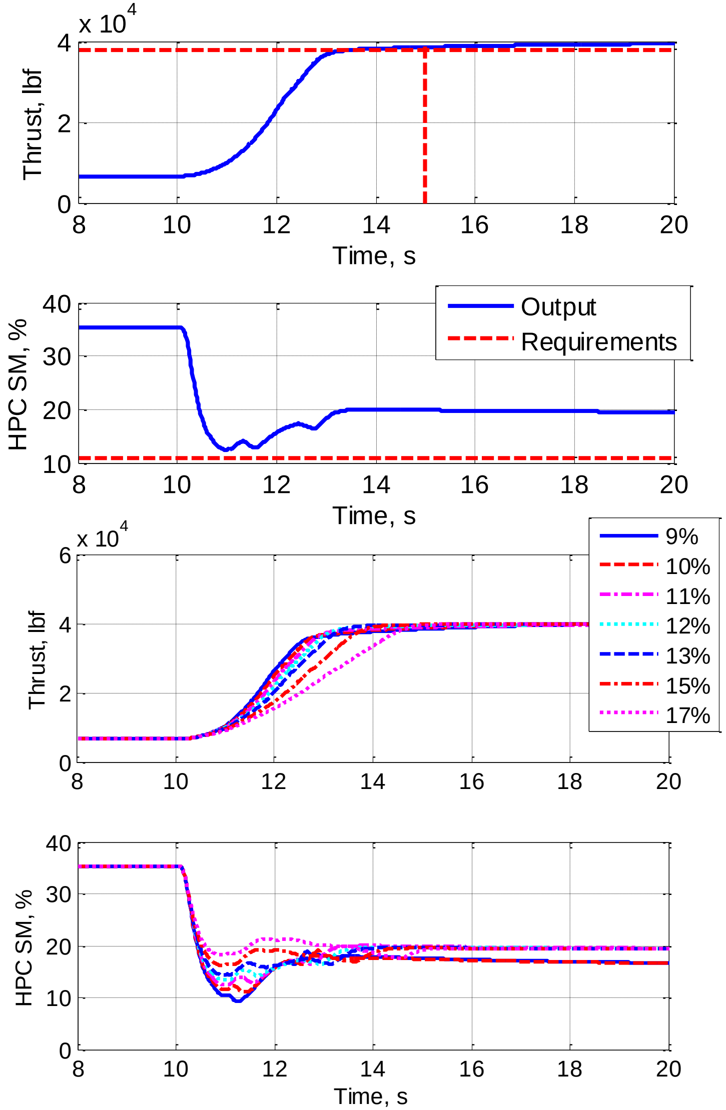


Commercial Modular Aero-Propulsion System Simulation 40,000 (C-MAPSS40k)

- 40,000 lb Thrust class high bypass turbofan engine simulation
- MATLAB/Simulink environment
- Publicly available to US Citizens
- Realistic controller
- Realistic surge margin calculations



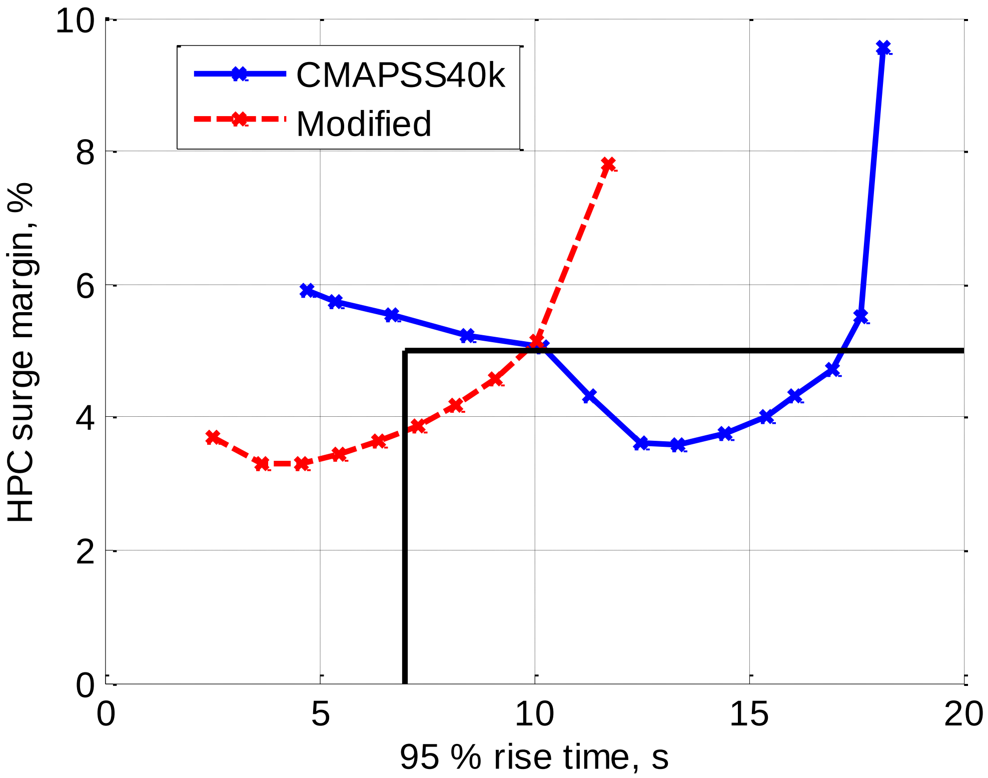
TTECTrA Output



- TTECTrA designs a controller to meet the defined control objectives and simulates closed loop response.
- Redesign control for varying operability constraints and observe closed loop performance.

Mechanism for Analyzing Turbine Engine Dynamic Performance

- Analyze closed-loop dynamic performance and operability margin.
- Compare various engine designs or determine if constraints are conservative.



- Modified design has better efficiency in terms of TSFC at cruise and takeoff

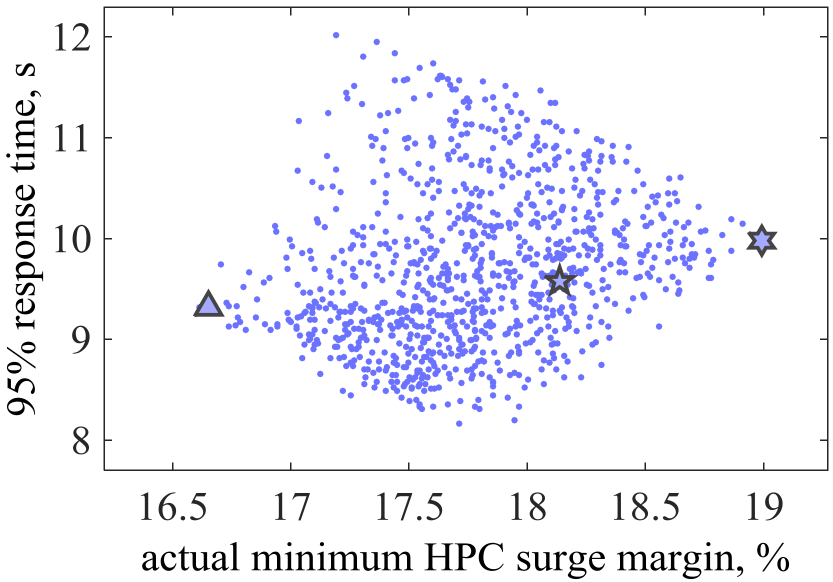
Csank, J.T, and Zinnecker, A.M., "Application of the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) for Dynamic Systems Analysis," AIAA-2014-3975, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.

Assessment to Meet Closed-loop Performance and Operability Requirement

- Closed-loop system should provide some guaranteed performance level throughout engine life cycle
  - Need a way to characterize effect of engine aging on performance level
  - Consider cases of random aging, rather than an assumed trend based on average/typical engine (more general description of aging)
- Develop metrics for describing the design requirements to meet this performance level and for comparing engine models

Data Collection

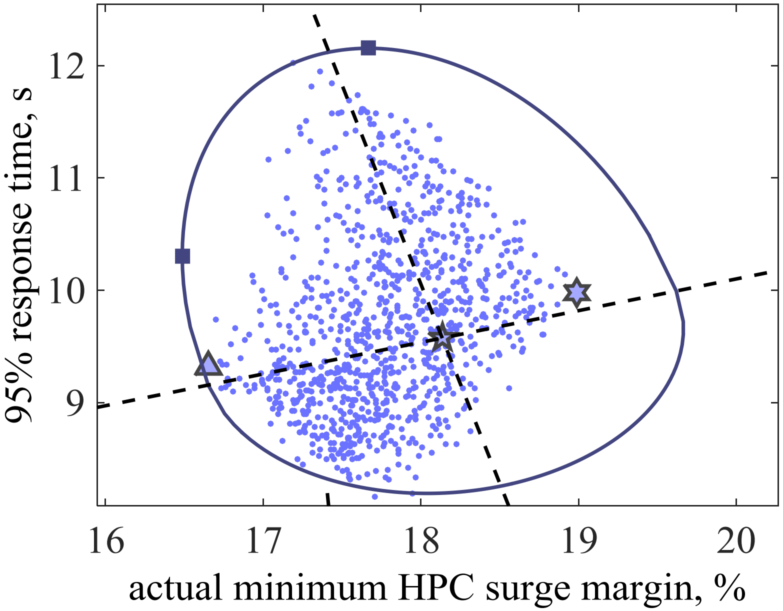
- Application of methodology requires an engine model that uses **health parameter** *h* to define engine age (deterioration)
  - h corresponds to efficiency and flow modifiers for each of the major turbo-machinery components
  - Each element of *h* is between 0 (new) and h_{eol} (end-of-life)
- Collect data from 2 sets of simulations
  - Known (anticipated) life conditions
    - New, mid-life, end-of-life
  - Randomly aged engines
    - independently, uniformly sample each element of h from 0 to h_{eol}



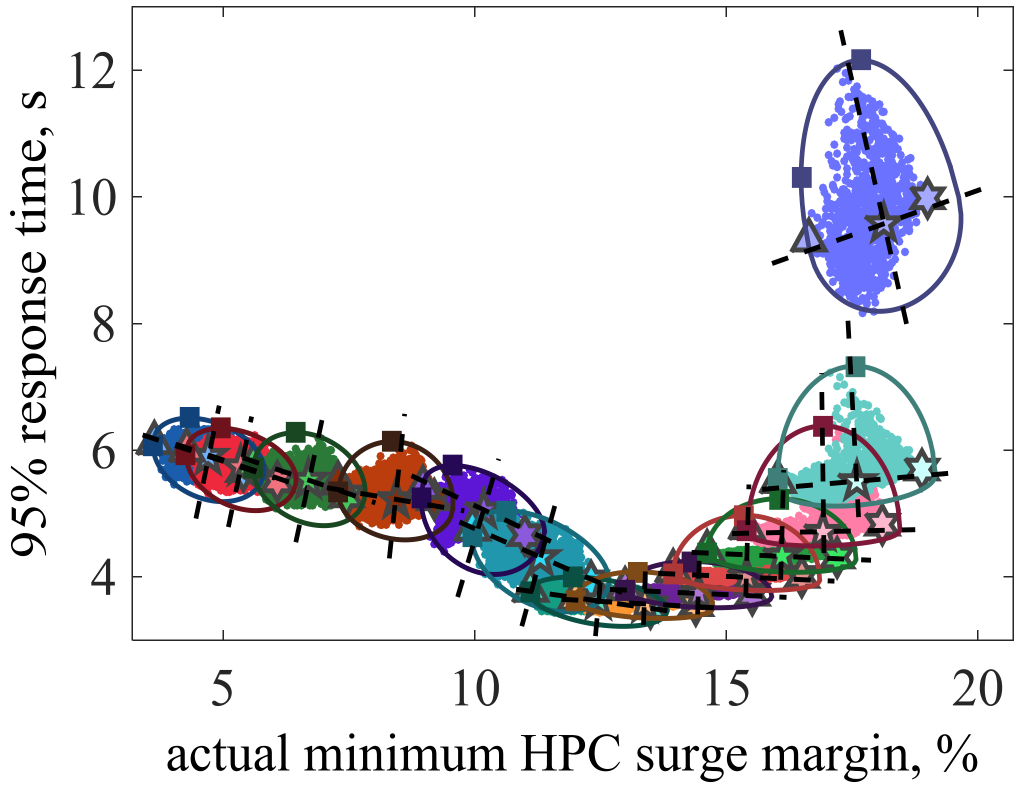
Defining Elliptical Boundaries on Performance Level

- Fit the Monte Carlo data at each trial design point into an ellipse
  - Length and rotation of ellipse x-axis based on new, mid-life, and end-of-life
  - Length of top- and bottom-half ellipse y-axes based on rest of Monte Carlo data

- Relate design point (*minSMd*) to performance level (*minSMa* and *tr*)
- Relate performance level to ellipse parameters
- Least squares approach to determine coefficients



Application of the Elliptical Boundaries on Performance Level

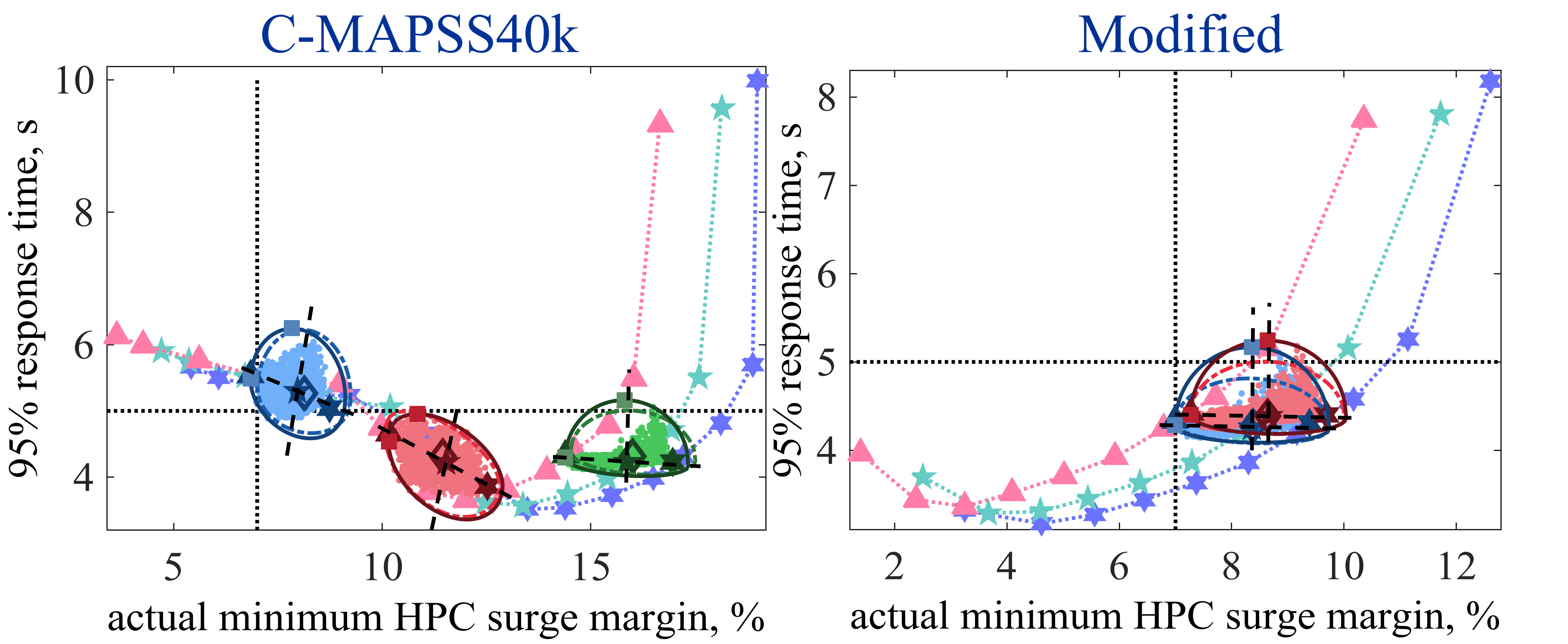


- Curve fit contains information regarding shape of nominal curve and how ellipse parameters change as function of design point.

Finding the Limiting Design Points

- Implement binary search procedure to estimate limiting design point meeting either minimum HPC surge margin or maximum response time limit.
  - Utilize curve fits and defined relationships to find design limit which meets either requirement.
    - Based on fixed number of design points and Monte Carlo simulations to evaluate each design point.
    - Reduces the total number of design points and simulations to evaluate engine design.

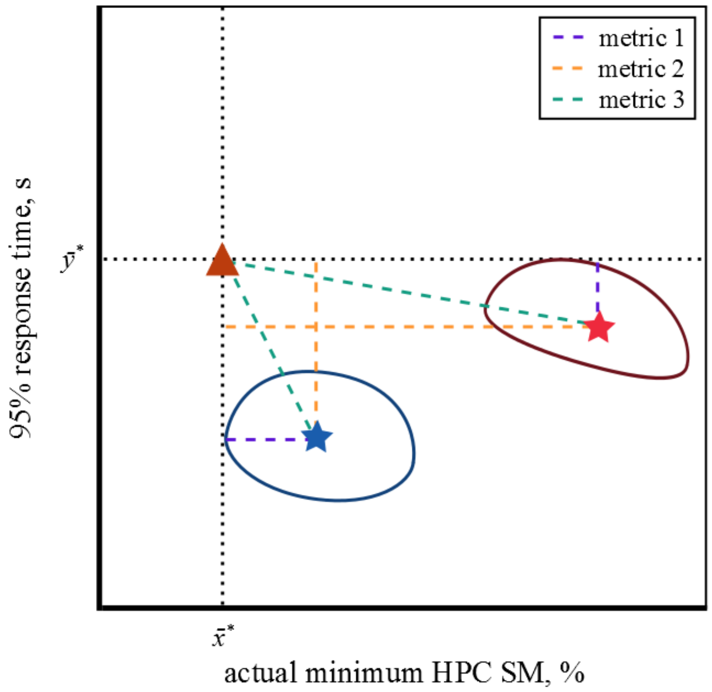
Application of the Limiting Design Points



- Compare both original C-MAPSS40k and modified version of C-MAPSS40k

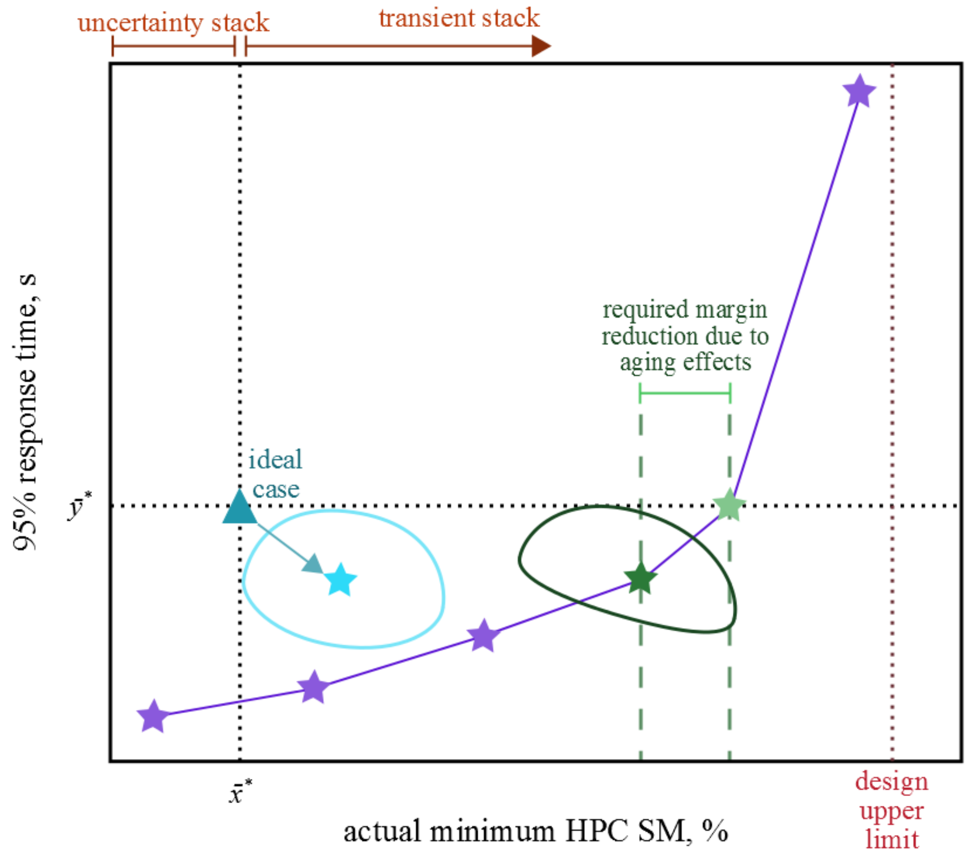
(Quantitative) Metrics for Comparison

- Three metrics defined to help compare models through performance-operability trade-off and robustness due to aging
  1. Distance from nominal to limit for which controller was designed
  2. Distance from nominal to limit for which it was not designed
  3. Distance from nominal to intersection of two limits



Benefit of Dynamic Systems Analysis

- Extremes
  - Small transient stack with a very long response time
  - Large transient stack with a very fast response time
- Known uncertainty stack
- Distance between uncertainty stack and the constraint is **transient stack**
- Faster response correlates to unnecessary transient margin.



- With ellipse, better define point near ideal operating point!
- Better defining transient stack required could allow design constraint to be adjusted and engine redesigned.

Summary

- Developed tools to analyze closed-loop dynamic performance and operability margin
  - **Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA)**
    - Design closed loop controller and analyze dynamic performance
  - **Assessment to Meet Closed-loop Performance and Operability Requirement**
    - Analyze performance and operability throughout engine life cycle
  - **Mechanism for Analyzing Turbine Engine Dynamic Performance**
    - Identify tradeoffs between dynamic performance and operability

References

- Users Guide: Csank, J.T., and Zinncker, A.M., "Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) Users' Guide," NASA/TM-2014-216663, June, 2014.
- Csank, J.T, and Zinnecker, A.M., "Application of the Tool for Turbine Engine Closed-loop Transient Analysis (TTECTrA) for Dynamic Systems Analysis," AIAA-2014-3975, 50th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cleveland, OH, July 28-30, 2014.
- Zinnecker, A.M., and Csank, J.T., "A methodology to assess the capability of engine designs to meet closed-loop performance and operability requirements," AIAA Propulsion and Energy 2015, Orlando FL, July 27-29, 2015
- Ozcan, M.F., Perullo, C., Tai, J.C., and Mavris, D.N., "Evaluating the Effect of Actuator Dynamics in Variable Area Fan Nozzle Gas Turbine Control," AIAA Propulsion and Energy 2015, Orlando FL, July 27-29, 2015

Thank you!

Any Questions?